Herbicide-Resistant Crops

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Abstract
The term herbicide-resistant crops (HRC) (sometimes termed herbicide-tolerant crops) has come to mean crops that have been genetically altered by biotechnology to be resistant to herbicides to which they are normally susceptible. Until the advent of plant biotechnology, selective herbicides were designed to kill important weed species while causing limited injury to major crops. Nonselective herbicides that kill almost all plant species were used only at times and places where crop injury was not a concern or with complicated application methods that avoided contact with the crop. There was little success in breeding crops for herbicide resistance especially to nonselective herbicides. Crops with genetics altered by biotechnology to impart herbicide resistance now offer the farmer valuable new tools for weed management. During the past few years, herbicide-resistant canola, cotton, maize, and soybeans have been widely adopted in North America and a few countries outside of North America. This technology has had many critics who have pointed out an array of environmental, toxicological, and societal risks.

CURRENT IMPACT ON WEED MANAGEMENT

The largest segment of the transgenic crop market has been HRCs. Several HRCs are currently available in North America (Table 1). At this time, the most widely utilized HRCs are those that are resistant to two nonselective herbicides, glyphosate (e.g., Roundup®) or glufosinate (e.g., Basta®). Glyphosate-resistant crops in particular have been widely adopted in cotton, soybean, maize, and canola in North America. In 1999, 55 and 37% of the soybean and cotton acreage, respectively, in the United State was planted with glyphosate-resistant varieties. An even larger proportion of the soybean crop in Argentina was glyphosate resistant. The use of glyphosate-resistant maize grew from 950,000 acres in 1998 when it was introduced to 2.3 million acres in 1999. The rapid adoption of glyphosate-resistant crops in the United State (Fig. 1) indicates that farmers find this trait to be very valuable. Other HRCs, such as bromoxynil-resistant cotton (Fig. 1), have been useful in situations with special weed problems. At this time, HRCs are not available to European farmers because of public resistance to their use.

RISKS AND BENEFITS

Generalities regarding risks and benefits of HRCs are difficult to make, as what is true for one HRC can be quite different for another, and even different for the same crop at another place or time. Furthermore, risks and benefits must be considered within the context of current and predicted future farming practices. These products are relatively new, and there are relatively few data to support predicted risks and benefits. Nevertheless, an attempt will be made to point out likely potential benefits and risks of particular HRCs. Many of these risks are being considered by regulatory agencies in their regulation of HRCs.

Benefits and Risks for the Farmer

A major benefit of the HRCs that are resistant to nonselective herbicides (glyphosate and glufosinate) is that the herbicide kills all or almost all weeds. Thus, in these crops, one herbicide can substitute for several selective herbicides that were needed to manage an array of weed species. Furthermore, glufosinate and glyphosate are used as foliar sprays after the weeds have appeared. Theoretically, the farmer can avoid prophylactic herbicide treatments and only rely on the nonselective herbicide after the weed problem appears. Some weed species, however, require relatively high rates of glyphosate for adequate control. In these cases, farmers are finding that the most efficacious weed management with glyphosate-resistant crops sometimes requires use of a selective herbicide with glyphosate.

Perhaps one of the most attractive features of being able to apply nonselective herbicides directly on the crop is that it greatly simplifies weed management, eliminating or reducing the need for tilling, for applying preemergence herbicides, and for decisions as to which selective postemergence herbicides should be used. Management simplicity favors

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Table 1 Herbicide-resistant crops available in North America.

Herbicides	Crop	Year	Resistance mechanism
Bromoxynil	Cotton	1995	Enhanced degradation
Sethoxydim[a]	Maize	1996	Altered target site
Glufosinate	Maize	1997	Altered target site
	Canola	1997	Altered target site
Glyphosate	Soybean	1996	Altered target site
	Canola	1997	Altered target site and enhanced degradation
	Cotton	1997	Altered target site
	Maize	1998	Altered target site
Imidazolinones[a]	Maize	1993	Altered target site
	Canola	1997	Altered target site
Sulfonylureas	Soybean	1994	Altered target site
Triazines[a]	Canola	1984	Altered target site

[a]Not transgenic.

the small farmer who cannot afford crop protection consultants.

Despite the fact that U.S. farmers have had to pay for both the herbicide and a technology premium for the HRC seeds, glyphosate-resistant crops have significantly lowered the cost of weed management. In soybeans, these costs have been lower than conventional weed management costs, resulting in the prices of herbicides for use in non-HRC soybeans being substantially lowered. Thus, HRCs have lowered the cost of weed management for all soybean farmers, whether or not they plant a glyphosate-resistant crop.

Many selective herbicides are not entirely selective, causing some phytotoxicity to the crop at certain doses under some conditions. Farmers have learned to accept this because the crop usually outgrows the effect, and there is rarely any significant crop loss. Nevertheless, farmers prefer to have no crop injury from herbicides. HRCs eliminate or greatly reduce crop injury by herbicides at early stages of development. Whether occasional developmental abnormalities in later stages of glyphosate-resistant cotton are due to glyphosate or not has been a contentious issue.

Both glyphosate and glufosinate have activity against some fungi and microbes. There have been reports that, in addition to killing weeds, glufosinate can reduce certain plant pathogen damage to some HRCs. This type of unpredicted benefit has been understudied. There are some potential problems for farmers with HRCs. If a farmer rotates HRC crops (e.g., maize after soybeans) that are resistant to the same herbicide, the unharvested seed of the previous crop can result in a serious weed problem. Evolution of resistance to herbicides is a growing problem, although not to the extent of insecticide or fungicide resistance. Evolution of resistance to glyphosate has not been a significant problem, despite the heavy use of this herbicide over a long period. A bigger problem has been weed species shifts in glyphosate-resistant crops to those species that require higher doses for adequate management (e.g., *Amaranthus rudis* in soybeans). In some crops, the transgene may be introduced into a sexually compatible weedy relative (introgression), creating the need to use additional herbicides. This has not been reported yet, but it will occur eventually if reproductive barriers are not incorporated into certain HRCs.

Glyphosate and glufosinate are commonly sprayed over the tops of the HRCs as a foliar spray. Spray drift to nontarget plants, including other crops, has been a problem since selective herbicides such as 2,4-D were introduced. The potential adverse impact of spray drift is increased when nonselective herbicides are used, in that only the transgenic cultivars of the crop are resistant. The potential of a severe herbicide application error is compounded when the HRC and non-HRC varieties are grown in close proximity.

Adoption of HRCs largely has been driven by short-term economic advantage for the farmer. As mentioned above, the replacement of other herbicides by glyphosate has reduced the value and price of competing herbicides. Furthermore, the price of glyphosate has steadily declined due to the expiration of its patent. Herbicides are the largest segment of the pesticide market. Thus, a major portion of the pesticide market has been significantly devalued, resulting in an escalation of the horizontal integration of the pesticide industry. Fewer companies and the devalued herbicide market will ultimately result in fewer herbicides from which to choose. The impact of this situation on farmers' abilities to cope with new weed problems and on the development of nonchemical weed management alternatives is difficult to predict.

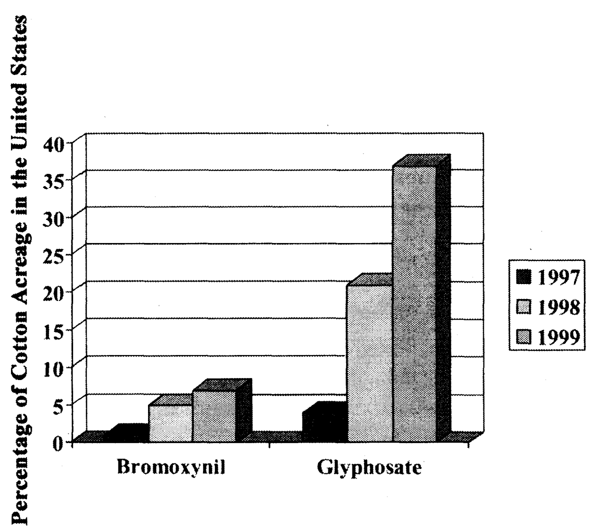

Fig. 1 Adoption of bromoxynil-resistant and glyphosate-resistant cotton in the United States during the last three years of the twentieth century.

Environmental Benefits and Risks

Other than removing land from its natural state, the primary long-term environmental damage of most agriculture has been soil erosion due to tillage. The soil that moves from plowed fields during rainfall events is often contaminated by pesticides, contributing to surface water contamination. The biggest hindrance to adoption of reduced and no-tillage agriculture has been inadequate weed management. The postemergence herbicides to which HRCs have been engineered allow farmers to reduce or, in some cases, eliminate tillage, thereby reducing soil erosion.

The leading HRCs are those resistant to glyphosate and glufosinate. These herbicides are among the most environmentally benign herbicides available. Both are amino acid analogues that degrade rapidly in the environment. Glyphosate is virtually inactivated upon contact with soil, due to its ability to bind soil components strongly. Both are toxicologically safer than most of the products that they replace, despite being relatively high dose rate herbicides.

A transgene that confers herbicide resistance represents a new potential threat to the environment. In some crops such as canola (*Brassica napus* L.), the transgene can introgress into weedy relatives. The herbicide resistance transgene confers no advantage to the weedy relative in a natural ecosystem. It can, however, favor the introgression of other transgenes of clear value in the wild (e.g., Bt toxin) that are packaged with the herbicide resistance gene. In the agricultural setting, all offspring of the weedy relative that are not a result of a cross are killed by the herbicide. Such a process could eventually lead to movement of trangenes of great survival value into natural populations, leading to significant natural ecosystem disruption. Reproductive barriers can be engineered into crops with introgression potential.

The vast majority of cropland in North America is devoted to agronomic crops and weed management in these crops is almost completely dependent on herbicides. Herbicides are expensive, but there are no economical alternatives to herbicides for weed management in these crops on the horizon. Thus, HRCs have simply substituted one herbicide for another. Studies done so far show little or no overall reduction in herbicide use rate (mass per unit area) with HRCs. However, the herbicides used with the most accepted HRCs are generally less environmentally suspect than the herbicides that they replace. For example, in maize and soybeans, glyphosate and glufosinate replace herbicides such as triazines and cloroacetamides that have generated environmental and toxicological concern.

THE FUTURE

Without public opposition, availability of currently available and future HRCs would eventually result in almost universal use of these products in all major crops. Growth of the adoption of HRCs will, however, depend on more than their value to the farmer. In a world economy, the rejection of transgenic crops by the European public could have a profound influence on their utilization in exporting countries such as the United States, even if there is relatively little opposition to their use where they are grown. Public opinion where they are now accepted could change. Whether HRC use increases or decreases is unlikely to significantly influence reliance on herbicides for weed management in major crops. New technologies such as precision agriculture and decision aid programs for weed management will, however, reduce both the volume of herbicides used and their environmental impact.

BIBLIOGRAPHY

Dekker, J.; Duke, S.O. Herbicide-resistant field crops. Adv. Agron. **1995**, *54*, 69–116.

Herbicide-Resistant Crops—Agricultural, Environmental, Economic, Regulatory, and Technical Aspects; Duke, S.O., Ed.; CRC Press: Boca Raton, FL, **1996**.

Dyer, W.E.; Hess, F.D.; Holt, J.S.; Duke, S.O. Potential benefits and risks of herbicide-resistant crops produced by biotechnology. Hort. Rev. **1993**, *15*, 367–408.

Hess, F.D.; Duke, S.O. Genetic Engineering in IPM: A Case Study. Herbicide Tolerance. In *Emerging Technologies for Integrated Pest Management. Concept, Research, and Implementation;* Kennedy, G.G., Sutton, T.B., Eds.; American Phytopathology Society Press: St. Paul, **2000**; 126–140.